FRP COMPOSITES TECHNOLOGY BRINGS ADVANTAGES TO THE AMERICAN BRIDGE BUILDING INDUSTRY

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ABSTRACT

Over the past six years of implementing the Innovative Bridge Research and Construction Program under the Transportation Equity Act, Fiber Reinforced Polymer (FRP) composites technology have successfully demonstrated its potential for structural applications in bridges. The Federal Highway Administration (FHWA) has funded over 120 projects scattered throughout the United States and subject them under different environmental and service conditions. This paper will present some samples of the bridge applications using FRP composites in deck systems, bonded repairs and strengthening, and prestressed applications. Some focused discussions on bonded repairs and strengthening will be presented because there is a greater need to maintain and upgrade existing bridges. It will also focus on what the Federal Highway Administration has done and continues to do to advance these innovative materials in the near future. Development of design specifications, guidelines and materials and testing standards are in the works. The rebuilding of the Nation's highway system and aging infrastructure presents a tremendous market opportunity for FRP composites for the 21st Century.
Keywords: FRP Composites, Bridges, Truss, Decks, Repairs, Strengthening, Hybrid systems

INTRODUCTION

The Federal Highway Administration (FHWA) manages a Federal-aid bridge program with an inventory of 600,000 bridges, each of which being greater than 20 feet in length. The average age of a bridge on the U.S. Interstate System is 45 years old. The Federal Government spent $4 Billion per year through apportionments during the 1998-2003 Transportation Equity Act of 21st Century legislation (TEA-21). The states and local agencies spent about the same amount from their combined matching shares and other tax revenues, thus doubling the annual spending to $7-$8 Billion for bridge improvement.

The highway infrastructure continues to face numerous challenges, i.e., increasing growth demands and heavier trucks as well as trying to preserve aging and rapidly deteriorating highway bridges. As we enter into a new millennium, our strategy is to stay ahead of the bridge deterioration curve by focusing on the use of emerging high performance structural materials and innovative quality designs for more durable and reliable structures. The TEA-21 legislation launched an important initiative and established the Innovative Bridge Research and Construction (IBRC) Program, which provided $108 million over six years to advance high performance materials in bridge applications. The IBRC Program was one of the largest Federal Government funded initiatives in the world; it was crafted to seek new and innovative material technologies for building more durable and effective bridges as well as extending the service life of the continually aging bridge inventory.

FIBER REINFORCED POLYMER COMPOSITES MET THE CHALLENGE

Through this pursuit and among many other emerging new materials, the fiber reinforced polymer (FRP) composite technology has been demonstrated with great success for bridge applications. FHWA has been developing research in FRP composites materials over the past 25 years. The development of the advanced FRP composite technology from the aerospace stealth aircraft and commercial industries is an engineer's dream for innovative structural design and application. It has been found that the characteristics of a composites element or system can be tailored and designed to meet any desired specifications. The highly corrosion and fatigue resistance composites materials are making inroads into the civil infrastructure industry. These outstanding composites are among the leading materials in structural engineering applications today.

In the six-year period, the IBRC program funded 246 proposals of high performance materials and concepts in bridge design and construction. Of these applications, 127 are constructed with FRP composite materials. Some of the applications have been or are being demonstrated consistently in several states to capture the performance of the FRP composites under variable environments and to spread the wealth of knowledge gained.

This paper not only discusses the different methods of applying the FRP composite materials but also lists the characteristics, advantages, disadvantages, and opportunities. The author will offer some closing thoughts and recommendations to the engineering community of what additional effort is needed to advance FRP composites into conventional practice. For the purpose of discussions in this paper, bridge applications using FRP composite materials can be categorized into four general groups:

- New bridge construction with bridge deck systems
- New bridge construction with hybrid materials
- Bridge strengthening and/or repair
- Seismic column retrofit

NEW BRIDGE CONSTRUCTION WITH FRP DECK SYSTEMS

About 30 percent of 600,000 bridges are being classified as either functionally obsolete or structural deficient. That does not mean that the deficient bridges are unsafe; they are classified administratively to indicate they require some form of maintenance or major rehabilitation to restore them to their original condition or to their original load carrying capacity. Many bridges have a superstructure consisting of concrete or steel girders topped with a concrete deck. Typically, a concrete bridge deck has a 25 to 40-year life span. In states where deicing salt is heavily used during winter operations, concrete bridge decks that were reinforced with unprotected steel reinforcement are deteriorating rapidly. The FRP composite deck systems have a potential to fill the need of bridge deck replacement and extend the service life of existing structures.

In the new bridge construction category under the IBRC Program, 44 projects employed FRP composite bridge deck systems that come in different shapes and forms. Most of these deck systems are proprietary products that were made of glass fibers and polyester or vinyl ester type resins. Some of these systems are into their third or fourth generation developments and improvements. They were made into either full depth sections to conveniently match the typical existing concrete bridge deck or partial depth sections.

Full depth (minimum 203 mm) panels are formed with pultruded structural shapes and shop-fabricated into modular panels for easy transport and rapid deployment. The cross section geometry takes the form of a truss configuration (top and bottom chords with diagonals, triangles, delta frames, “X-shaped” or other similar variations). The panels are spliced together in the field and are normally fastened onto a floor-beam and/or stringer structural support system. Another deck system is of built-up pre-cured sections consisting of orthogonal, honeycomb cells that act as the core element and sandwiched between two face sheets. A third system consists of a single stage large piece fabrication involving lay-up glass fibers, wrapped hollow cores, and vacuum assisted resin transfer molding. A fourth system, which is a shallower section, is constructed with side-by-side, parallel (127 mm X 127 mm) pultruded tubes acting as the core element and sandwiched between two face sheets. A fifth system is a FRP composite sheet panel stiffened with pultruded tubes placed transversely to the traffic direction. The tubes serve as tension reinforcement in the positive moment region, and the panel serves as a permanent bottom form for a cast-in-place full depth concrete deck. This system requires additional FRP composite reinforcing bars in the top mat.

An excellent example of an effective application with the FRP composite deck system is the replacement of an existing conventional concrete deck on a 60-year old, Warren steel truss. The 34.7-meter simple span truss was posted with a 12.7-metric ton weight restriction. Over the years of resurfacing the roadway and deck, the structure had accumulated numerous layers of asphalt cement, thus reducing its live load capacity. By replacing the deck with FRP composite deck panels, the existing 830-kg/meter^2-superstructure dead load was reduced to 171 kg/meter^2. The bridge was immediately upgraded to carry more than the current legal load. The removal and replacement of the deck system took less than a month to complete. The cost of the rehabilitation ($876,000) was about one-third the cost of total replacement ($2.34 million) and was fully funded by the New York DOT [1].

The advantages of an FRP composites deck are lightweight, high strength and high performance, chemical and corrosion resistant, easy construction and handling, rapid project delivery, and in most cases, high quality shop fabrication. Its lightweight (88-171 kg/meter^2 without a wearing surface overlay) reduces the overall superstructure weight and foundation requirement. In areas of high seismic zones, a reduced mass may be highly desirable. Although the composite materials are of high tensile strength, the current deck design is governed by stiffness requirements. The stiffness modulus of glass FRP composites is about one-fifth that of steel. Except for high or ultra high modulus carbon materials, the stiffness modulus of typical carbon fibers is slightly higher than structural steel.

Another important feature of the FRP deck panel systems is its ability to be rapidly deployed and installed at the job site. In reducing congestion in the work zone and improving safety, FRP bridges that had been built from a relatively few short hours to over a weekend are highly desirable and sought after. Bridge owners are willing to pay some premium upfront cost over conventional method of construction that requires prolonged duration. The author predicts that in 10 years from now, long delays through routine construction work zones will no longer be tolerated.

There remain some challenges in the use of FRP composites for deck replacement. The design of an FRP deck system requires finite element analysis. Its lightweight in the superstructure can become aerodynamically unstable, especially for long span structures. As in any new innovation and being an anisotropic material, the composite components and system would require validation testing while building up a good database for each specific system. Depending on how a deck panel is fabricated, consistency and quality may vary. For field installation, connections and some other construction details would need to be developed, improved and tested. A well-designed and properly installed thin bonded overlay can improve traffic traction and extend the service life of the deck panels. Traffic railing connections would need to be designed and tested for crash worthiness. Nondestructive testing/evaluation devices should be incorporated into inaccessible parts of the deck panels to monitor short and long-term performance and to facilitate maintenance inspection. These disadvantages should not be viewed as hindrances. Rather, they should be welcomed as development opportunity for the engineering community and industry. As structural engineers learn more about the behavior of the composites, these problems will be resolved through proper applications, detailing and further research.

The FHWA desires to advance the FRP composites deck applications into conventional practice and is working with the AASHTO Technical Committee to develop guide specification for testing and acceptance of the deck systems. This will include testing standards and protocol to establish strength and stiffness requirements, connections and joints, and manufacturing variations and acceptable defects. The goal of this study is to develop performance specifications that will help bridge owners gain confidence in using composites. The research has been completed and a draft guide specification has been undergoing some peer reviews. A final draft will be submitted to the AASHTO Technical Committee for further review beginning 2004.

NEW BRIDGE CONSTRUCTION WITH FRP HYBRID SYSTEMS

The United States bridge construction technology and philosophy is based largely on a first-cost basis. Since FRP composite materials have a higher first-cost, hybrid FRP systems that combine the high stiffness and/or high compression strength of conventional materials have been proven effective. Hybrid systems may be classified into two categories – structural composites product with hybrid fibers and structural systems consisting of hybrid composites and conventional materials. The first category involves a product-level definition that is made by combining carbon and glass and/or aramid fibers and resin to form a unidirectional structural element such as laminate or thin plate, rod or tendon, and strand. The second category involves a system-level that is defined by incorporating FRP composite components into a structural member made of conventional materials.

When designing hybrid structures, the key is to strategically place the FRP composites where its high tensile strength can be capitalized, while taking advantage of the high compressive strength and/or high stiffness of conventional materials. The high tensile strength of FRP composites is derived from its unidirectional fibers parallel to the axis of the applied load. In contrast to the high compression strength in concrete, the FRP fibers contribute to the composites' high tensile strength but the resin matrix contributes only a fraction of its compression strength. The use of hybrid systems would help build confidence in conservative bridge engineers who are more comfortable with conventional materials.

In hybrid product systems, the FRP composites are fabricated to form reinforcing bars, tendons, laminates or two-dimensional grids, gratings or flat plates using carbon and/or glass fibers. In bridge applications, the author has seen hybrid fibers being used in wet lay-up fabrics more often than in unidirectional elements. A three-dimensional fabric structure would include grid or cage systems. Although they exist, the author has not yet seen these types of systems being used for bridges.

FHWA is committed to promoting durable bridges. The short life span of conventional steel reinforced bridge decks in a highly corrosive environment attributed to heavy deicing salt use during winter weather operations is unacceptable with today's traffic capacity demands in developing communities. On Federal-aid bridge projects, there is a requirement for corrosion protection strategy (e.g., water proofing membranes and overlays, epoxy coated rebar, concrete cover) for concrete bridge decks. FRP composite reinforcing bars could have a niche for those who are satisfied with the reinforced concrete decks. The unidirectional fiberglass rod may either be coated with sand and/or treated on the surface to mimic the deformed steel bar for enhanced bonding with the concrete matrix. Carbon fiber rods and grids are being demonstrated in some projects. The National Cooperation of Highway Research Program under the Transportation Research Board (NCHRP-TRB) has completed a research study to develop material specifications on FRP composite materials as concrete reinforcing elements. This project has been completed and a report is available through the NCHRP-TRB.

There had been some reported corrosion problem in steel tendons that caused bridge failures in conventional prestressed concrete applications in the U.S. and Europe. Some states have reported corrosion and broken steel tendons in segmental concrete and pedestrian bridges recently. Others have detected voids in grouted post-tensioning ducts. The highly corrosion resistance FRP composites, high strength tendons are showing great potential in prestressed applications. A unidirectional carbon fiber tendon coupled with high performance concrete would eliminate corrosion problem and enable concrete members to last 100 years. One such successful first generation application in pre- and post-tensioned concrete Tee beams is proving that the FRP composites can be designed to overcome its non-ductile behavior. Although an FRP composite component behaves linearly elastic until rupture, it can be designed to behave in a ductile manner in a structural system. By combining both bonded and unbonded tendons in double-Tee prestressed concrete beams, Professor Grace, Lawrence Technological University in Michigan, has demonstrated that the hybrid concrete/FRP composite tendons concrete structural system can be designed to fail with large deflections [2].

The challenge is to develop efficient and effective anchorage systems for prestressed applications. Current proprietary anchorage systems consisting of various bonded sockets or metal sleeves served as a good start to demonstrate their applications. However, these first generation systems may have undesirable creep in both the resin matrix and adhesives, potential corrosion in the metal sleeves, and shear lag phenomena. Improvement in these areas would propel the advancement of prestressed applications. The FHWA has completed a research study that includes design guide and specifications. The goal of this study is to develop recommendations and guidance for applying FRP prestressing tendons and anchorages in bridges. More information will soon be made available with the release of an FHWA report. ACI 440 has an active working subcommittee for prestressed applications and some guidelines development may be already at work.

In the past few years, there has been some interesting research and development in the glulam timber bridge technology. A thin GFRP laminate consisting two percent of the cross sectional area of a glulam timber beam placed at the extreme tension fibers can increase the flexural strength 170 percent. This hybrid FRP composites/timber beam would reduce the amount of timber material and overall first cost. When vertical clearance is not a problem, the hybrid beam of similar depth can be made to span longer. FRP composite laminates will allow designers to take advantage of the composites' high tensile strength with conventional but lower quality lumber.

The disadvantage in using unidirectional FRP composite rod and tendon elements as substituted materials is a weak commercial incentive. The Germans had developed a high quality prestressed fiberglass tendon, but it could not compete with the steel strand on a first cost basis. As a result, the GFRP tendon never had a chance to go beyond the handful of demonstration bridge projects built in Germany. It is hoped that a potential success in prestressed applications would advance the prestressing tendons into long span cable-stayed and cable suspension bridges. The FRP composites offer the potential to eliminate the problem of excessive cable dead load and corrosion problem on long span bridges. The Swiss constructed a cable-stayed structure replacing two of its 24 stay cables with CFRP materials to demonstrate that it could be done [3].

Other CFRP and GFRP cylindrical shells are also being used in pilings, crash cushion, and dolphin construction in brackish waters and land structures along the Eastern Coastal states. There is much research needed on design, installation, and connection details as well as durability with these applications in constant wet-dry cycle environment.

BRIDGE STRENGTHENING AND REPAIRS

The second leading application thorough the IBRC program is the bonded concrete repair using FRP laminates, rods and wet lay-up fabrics. The surface mounted composites have been used in numerous concrete bridge strengthening and repair applications. This technique is cost effective, easily to design, install and inspect. Composites applied to the soffit of existing concrete decks have been demonstrated and tested in Europe, Japan and America.

In general, when a structural member is being repaired using FRP composites, it will be much stronger than its original undamaged condition. The FHWA tested to failure a repaired Type II, AASHTO prestressed concrete girder. The repair was hand-wrapped using CFRP fabric and epoxy adhesive system. The repaired beam was 130% stronger than its original design. In bridge strengthening, a reinforced concrete beam's capacity can be increased for shear and/or flexural loads. Concrete slabs could be strengthened for flexural loads. When properly designed and applied, repairs can be done successfully without having to completely replace the whole structure. The work completed by Professor Urs Meier, Swiss Federal Laboratories for Materials Testing and Research (EMPA) in Dübendorf, Switzerland, has provided some excellent guidance for strengthening of structural members with FRP composites [5]. To ensure structural integrity when strengthening existing structural members, it is important to maintain a factor of safety for the slab greater than or equal to 1.0 for the pre-existing reinforcement. The failure mechanism for bonded repairs takes on numerous paths and the effort to quantify the failure modes would require time and further research.

A good repair program should include an evaluation of the preexisting condition and structural integrity of the overall concrete member to establish a baseline reference. For surface mounted applications, the concrete surface requires some preparation to ensure the substrate is sound and of good structural integrity. Deteriorated concrete or delaminations must be removed. Spalled surfaces must be built up to provide a level and flat surface for bonding the aligned fabric sheets or laminate. Sharp edges and corners must be rounded to prevent a knife-edge action on the fabric. When using rods, grooves must be saw-cut in the concrete surface. Moisture problem must be corrected before using composites bonded repairs because ambient-cured organic material adhesives are problematic in wet environments.

For bridge decks exhibiting extensive cracking, covering the entire soffit completely is not advisable. Moisture can accumulate inside the cracks and freezes, aggravating the concrete deterioration. Bonded laminates spaced a distance apart or fabric sheets in grid pattern would allow moisture to pass through a cracked deck; however, long term durability of the bonded repair could be compromised if the unprotected steel reinforcement inside the concrete continues to corrode.

The author has seen surface mounted bonded repairs and strengthening in unreinforced masonry structures. Composites rods were embedded in saw-cut grooves in mortar joints of masonry walls to increase its shear and bending capacities. And if needed, vertical or skewed-angle rods were added to form a grid pattern. Earlier studies have shown that wet lay-up fabrics are effective. Open grid systems are more desirable where inspection access is unhindered.

The author believes that all structural repairs should be accessible for inspection, and some form of monitoring must be instrumented for inaccessible areas. After a structural member has been repaired, the in-service condition of the concrete substrate as well as the performance of the composites should be continuously monitored.

The Japanese used bonded repairs for strengthening their tall masonry, round smoke stacks. As those chimneys aged, they required some repair and strengthening to continue their safe operation today.

FRP chimney liners in service up to 20 years has proven FRP survival at high temperature, resistance to chemicals, structural reliability, low life-cycle cost, and low maintenance.

A technique using filament winding consisted of a machine equipped with spools of prepreg carbon tows and mounted on a guide system that winds around the chimney wrapping layers of carbon fibers onto the surface of the structure. The machine travels up and down to form a continuous shell and the prepreg is then cured in place. California used this similar technology to strengthen numerous bridge columns for seismic retrofitting. There will be more discussions of this topic further along in this paper.

The fiber wrap systems are also being used to repair deteriorated concrete piers, pier caps, concrete arch, and damaged beams. This technique is preferred for small and easily accessible locations because it requires only light duty equipment and small work crew. Furthermore, this technique indicates that numerous potential applications in civil engineering structure can be economical feasible and effective.

The FHWA has commissioned a research study through the University of Missouri at Rolla, Missouri to develop guide specifications. The American Concrete Institute, Committee 440 has developed and published design criteria and guidelines. In general, a beam or slab can be effectively strengthening to a greater capacity than its original design without significantly affecting its structural integrity from its secondary effects.

SEISMIC COLUMN RETROFIT

The development of the United States seismic design codes has been an evolving process, usually through the real test of time and seismic events. As a result of the Loma Prieta Earthquake in Oakland, the California Transportation Department (CALTRANS) has been leading the retrofit of concrete bridge pier columns using FRP composite materials. The piers that were designed under pre-1971 seismic design codes were found inadequate for shear capacity, ductility and confinement in plastic hinges. The CALTRANS had since retrofitted thousands of concrete pier columns using FRP composite materials. The manufactured products can be classified into three categories: filament winding, hand-wrapped fiber sheets, and pre-cured cylindrical shells. The seismic column retrofit using FRP composite materials has been through a great deal of testing and development, and this application has been accepted as an established method for column strengthening. A well-defined accelerated testing protocol of up to 10,000 hours of exposure to various environmental conditions has been developed by CALTRANS to estimate degradation over the projected service life. Other states are beginning to adopt it in their bridge column retrofit program.

SOME CLOSING THOUGHTS

We have made excellent progress with the FRP composites technology for bridge applications. The demonstration projects from the IBRC Program gave us a good start in adding FRP composites technology to our toolbox. The high strength, high fatigue resistance, lightweight, and corrosion resistance of composites are highly desirable characteristics for bridge applications. The author considers the sample applications are only a prelude as to what is more to come.

The FRP composite strengthening technology has proven successful, and we will probably see more applications in the future. When we have design and construction specifications developed and adopted, bridge owners will be able to extend the service lives of numerous bridges, landmark and historic as well as routine structures at a fraction of the bridge replacement costs.

We need to take research, development and applications into higher levels of exploitations. Long-term durability issues need to be defined because the materials do not have sufficient historical performance data in bridge applications. The last six years of demonstration in bridge applications in the U.S. and accumulative work of others worldwide will serve as a continuous study laboratory in the field. Bridge owners need assurance of long-term integrity of bonded joints and components under cyclic fatigue loading, and they have seen and like what composites have to offer. Improper curing of the resins and moisture absorption and/or ultraviolet light exposure of composites that may affect the strength and stiffness of the structural system should be addressed. Certain resin systems are found ineffective in the presence of moisture and the author believes inorganic resins may be the solution to this problem. We need to follow up and verify their performance and durability.

Currently, most of these new materials are a direct technology transfer from the aerospace industry, and they are far more advanced than those required by civil applications. Most of the advanced composite materials that are cured at high temperature produce high quality and possess excellent characteristics. In bridge applications, resins as the binders for the fiber and adhesives for joints and connections that can adequately cure at ambient temperature and still offer comparable quality and characteristics are more desirable and practical. Standardized bridge components and systems design would allow more focused research, development and competitiveness. More efficient manufacturing and effective production methods for large volume panels and higher modulus materials are needed to make it more cost effective for composites to compete in the civil infrastructure. The direct technology transfer of fiber composites from the aerospace industry is not cost competitive when compared to conventional materials in bridge applications.

REBUILDING THE U.S. TRANSPORTATION INFRASTRUCTURE

Those challenges mentioned above should not be viewed as barriers but progress to make good on what the materials have promised to deliver. They will serve as opportunities to improve the materials to ensure that the product will be durable and reliable. The current focus for FHWA is to advance the FRP composite technology to rebuild the American transportation infrastructure in new bridge construction as well as the rehabilitation and maintenance of the existing bridge inventory. The rebuilding of the Nation's highway system presents a tremendous market opportunity for those high performance materials in bridge applications well into the 21st Century.

CONCLUSION

The author has presented numerous successful examples of FRP composites bridge applications. FHWA is advocating structures that not only will last 100 years but also reliable and consistence in performance. The FHWA believes there is a great future with the composite materials and will continue to support research and development in future generations of FRP materials. ACI Committee 440 has taken up on the challenge and is developing some guidance in the use of FRP under its various subcommittees. Numerous publications capturing the success of the FRP composites used in the civil infrastructure are available through the ACI.

The FHWA is developing a database to capture the performance history, design guidelines and specifications used in the demonstration projects. Information is made available to anyone through our Website: **(www.fhwa.dot.gov/bridge/frp).** We welcome your input and contribution to help us capture and disseminate the knowledge.

The future is bright for FRP composite materials. It is an exciting time for bridge engineers, consultants, researchers and the FRP composites industry. With FRP composites, the Americans are already changing the way they build and maintain their bridges.

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